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APPLICATION OF CODE DIVISION MULTIPLE ACCESS
IN MICROWAVE AND SATELLITE COMMUNICATIONS

by

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APPLICATION OF CODE DIVISION MULTIPLE ACCESS IN MICROWAVE AND SATELLITE COMMUNICATIONS

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ABSTRACT

This article presents a brief introduction to the basic concepts of code division multiple access and the principles, block diagrams and some parameters of applying pseudo noise phase shift keying code division multiple access and pseudo random frequency hopping modulation code division multiple access in satellite communications.

I. Introduction

The special characteristic of code division multiple access (CDMA) is that the signals sent by each station on the net use the same bandwidth (normally using the entire relay bandwidth, but it may also be a portion of the relay bandwidth) and sending at any time. Each signal is alternately distinguished by relying on the "permission" of he structure. The basic modulation method for CDMA is spread spectrum modulation, that is, for each station, the radiating frequency spectrum used is much larger than the spectrum ordinarily required for the information (several magnitudes larger), so the MCDA cal also be called spread spectrum multiple access (SSMA). The pattern (that is, the signal structure) of spread spectrum modulation is called code. The receiving station must generate and use a code which is exactly the same as the code of the transmitting station to be able to receive and modulate this spread spectrum modulated signal. For other receiving stations using different coding, this spread spectrum modulated signal

appears as random, wide band noise.

The primary advantages of CDMA are:

1. Flexibility in operations, not requiring complex dynamic adjustment between stations such as not requiring the entire net to be synchronized.

2. As the number of stations communicating at the same time decreases, the quality of communications automatically improves.

3. It has strong counter interference properties (it can handle pre-selective attenuation, multi-radius broadcast and artificial narrow band interference).

4. It is secure.

Its disadvantages are:

1. Data rate is low (or uses many bandwidths).

2. Equipment is rather complex and expensive.

3. It requires channels be synchronized (that is, synchronized between sender and receiver).

4. It requires control of upgoing power (or certain stations will make excessive use of satellite output power).

Clearly, overall code division multiplex is suitable for military communications.

There are two primary types of spread spectrum modulation, one

being the use of phase shift keying, commonly called pseudo noise or pseudo random phase inversion, and the other uses frequency shift keying, commonly called frequency hopping. These two methods will be addressed below.

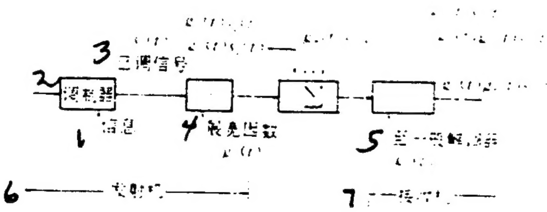
II. Pseudo noise phase shift keying code division multiple access

The principles of operation of pseudo noise phase shift keying code division multiple access (PN/PSK/CDMA), simply stated, are to digitize information and load it onto a pseudo noise code (sequence) generated by a pseudo noise sequence generator (usually one information byte and many pseudo noise code bytes are combined), and then spread by this spectrum, a signal with random noise characteristics is used to phase modulate (usually phase inversion) the carrier wave, generating a spread spectrum modulated carrier wave. At the receiving terminal, there is a similar pseudo noise sequence generator. It is synchronized with the pseudo noise sequence generator at the transmitting terminal, and generates the same pseudo noise code. By using this for phase inversion demodulation and reception of the carrier wave, and then removing the pseudo noise code from the signal, the required information is demodulated. At the same time, each pair of ground stations using the same frequency bands, using different pseudo noise codes to differentiate the station addresses, it is possible to realize multiple access communications. The code division multiple access signals transmitted by other stations on the same frequency band becomes, for this receiving station, harmless wideband noise, most of which is not able to enter the intermediate frequency band of the receiver. Although there is a certain amount of mutual interference between different pseudo noise signals, the amount of interference between any two pseudo noise signals is actually very small. Naturally, the number of pseudo noise signals which a specific channel can hold (that is, the number of ground stations

on the same spectrum) is limited.

1. Phase inversion modulation of the pseudo noise sequence

Fig. 1. General spread spectrum system



1. Information. 2. Modulator. 3. Modulated signal. 4. Spread factor. 5. To modulator. 6. Transmitter. 7. Receiver

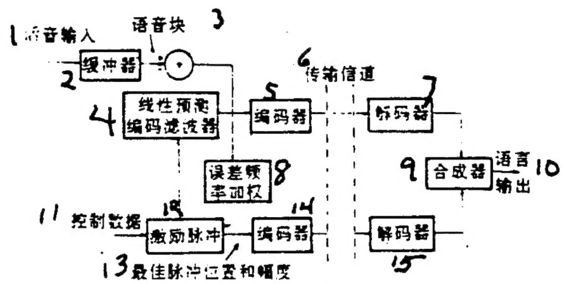
Figure 1 is a block diagram of the most general spread spectrum system. In this diagram, the carrier wave is modulated by the information using a common method, generating a modulated signal ($s_1(t)$. Then it is linearly multiplied by a certain spread factor (pseudo noise sequence) $g_1(t)$, resulting in $g_1(t)$ diffusing the energy of the $s_1(t)$ signal so that it occupies a bandwidth much wider than the original modulated signal. $g_1(t)s_1(t)$ passes through the information channels and here it is linearally combined with other signals $g_2(t)s_2(t)$, $g_3(t)s_3(t)$, ... $g_n(t)s_n(t)$. All signals are transmitted using a common carrier wave. A composite signal is received at the receiving terminal. The task of the receiver is to select the required signal $s_1(t)$ from the composite signal, suppressing all the other signals. Therefore, the receiver itself generates a $g_1(t)$ (pseudo noise sequence) exactly like that of the transmitting terminal, multiplies this times the composite signal, with a resultant output of:

Desired signal $= g_1^2(t)s_1(t)$

Undesired signal = linear combination of $g_1(t)g_2(t)s_2(t)$, $g_1(t)g_3(t)s_3(t\_$, ... $g_1(t)g_n(t)s_n(t)$.

That is to say, a receiver with a $g_1(t)$ spread factor selects out the $g_1(t)s_1(t)$ signal, and other signals are not selected out. Next, we will summarize the shift inversion keying modulation commonly used in satellite communications to further explain this principle. Figure 2 uses a direct coding spread spectrum system (that is, using high speed coding to directly modulate the carrier wave. This is a system commonly used in pseudo noise methods, and is also called direct sequencing method. It commonly uses two phase modulators).

Fig 2. Direct coding modulation spread spectrum system

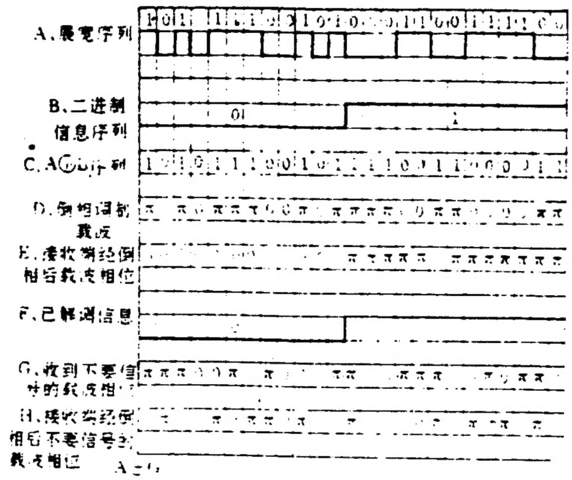


1. Voice input. 2. Buffer. 3. Voice module. 3. Linear prediction code filter. 4. Coder. 5. Transmission channel. 6. decoder. 7. Error frequency weighting. 8. Synthesizer. 9. Voice output. 10. Control data. 11. Excited pulse. 12. Maximum pulse position and amplitude. 13. Coder. 14. Decoder.

Binary information sequence **(a_1)** passes through the phase inversion switch and modulates the carrier wave. When the binary modified information is zero, the carrier wave phase is not changed (it is zero degrees), when the information is one, the carrier wave phase changes 180°. The modulated signal **$s_1(t)$** passes through the

second phase inversion switch and multiplied by the spread binary sequence, that is, it is phase inverted once more using the spread $s_{1(t)}$ signal pseudo noise sequence. Actually, it is the combination of the information sequence and spread sequence, and then modulated onto the carrier wave with phase inversion keying. The up-converted spread signal is then transmitted over a communications channel using ordinary means. At the receiving terminal the signals received is down converted to a suitable intermediate frequency and then frequency inverted using a locally generated spread sequence which is the same as that of the transmitter (here, because the sequence received and the sequence generated locally are correlated, it can be called receiver correlator). The result of the phase inversion cancels out the phase shift added by the transmitter, and restores the original information sequence. This process is shown in Figure 3. As for other signals which are transmitted on the same channel, they appear as high speed phase inversion modulated signals at the output of the receiver correlator because they have been spread by different spread sequences. That is, as a pseudo noise sequence, but not restored to the original information.

Fig. 3. Correlator demodulator receiver process



A. Spread sequence. B. Binary information sequence. C. A⊕B sequence. D. Phase inversion modulated carrier wave. E. Receiver terminal carrier wave phase after phase inversion. F. Demodulated information. G. Carrier wave phase of unwanted signals. H. Receiver terminal carrier wave phase of unwanted signals after phase inversion.

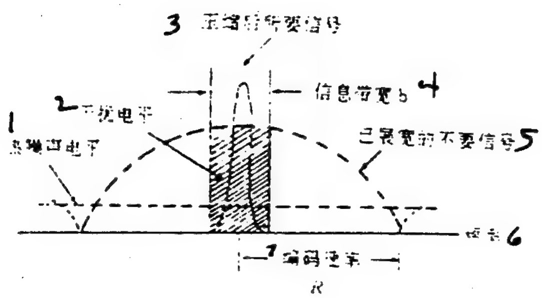
2. Counter interference properties of spread spectrum signals

The criterion for measuring a numerical system's capabilities is the bit error rate. The error rate P_e is reduced as the ratio of the information energy to the total noise energy spectrum density E/N'_0 is increased. If interference signal mean power is limited (man-made noise), it can greatly exceed the spread signal energy far beyond the band width required by the information wave form, and cause P_e to decrease. A number of interference signals whose mean power is limited can be spread on the same band width just as the desired signals, thus reducing the power spectrum density N'_0, and thereby reducing he effects of interference on the signal. This is the basic reason why when the signal bandwidth is increased when there is average power limited interference the

spread spectrum system is able to increase its counter interference properties.

As stated earlier, the composite signal including both the signal and noise sequence enters the receiver correlator, and after it is phase inverted by the locally generated pseudo noise sequence, what remains is the desired signal which enters the receiver intermediate frequency. The intermediate bandwidth is the same as that of the desired signal, thus the output is the desired signal. The unwanted signal, however, because the locally generated pseudo random sequence is not coherent, it remains a spread signal. We can see from Figure 4 that most of the interference signal is suppressed, and that only a small portion (the shadowed portion in the illustration) falls within the bandwidth of the receiver intermediate frequency. Clearly, the larger to ratio of the spread signal and the receiver intermediate bandwidth, the less interference is generated by unwanted signals. If this ratio is 100:1, that is, each byte is transmitted by 100 "shards" (sub-pulses), interference of the same strength as the desired signal would only be able to damage one sub-pulse in one byte. In order to destroy all sub-pulses, it would require interference 100 times as strong as the desired signal. This ratio of information bandwidth (modulated bandwidth) to spread signal bandwidth (transmission bandwidth) is the processing gain (also called the spread spectrum gain) of the spread frequency. There is a definite relationship between the spread frequency bandwidth and the spread code rate (also called the code clock rate or phase inversion rate). If it is binary, the pseudo random noise spread spectrum signal's bandwidth is twice the coding speed. If it is quaternary, the spread spectrum bandwidth is equal to the coding speed. If it is octal, the spread spectrum bandwidth is equal to 2/3 of the coding rate. The higher the spread spectrum processing gain, the stronger the interference.

Fig. 4. Correlated spectrum



1. Hot noise level. 2. Interference level. 3. Compressed desired signal. 4. Signal bandwidth b. 5. Spread unwanted signals. 6. Frequency. 7. Coding rate.

3. Code used in pseudo noise code division multiple access

Pseudo noise code division multiple access allocates one pseudo noise code, also called noise sequence (or pseudo random sequence) to each pair of stations. The same frequency band is used between each pair of station. This frequency band is completely filled with the pseudo noise sequence frequencies. Because the use of pseudo noise sequences exercises binary keying of the carrier wave, the signal spectrum is spread P times. P is the length of the pseudo noise sequence, so the code division multiple access is also called spread spectrum multiple access. Therefore, the code used by code division multiple access is pseudo noise coding or pseudo noise (pseudo random) sequence.

The recovery of the base band digital information from the spread spectrum carrier wave is done through what is called correlation processing. This is just like we discussed before, where the transmitted spread spectrum signal is multiplied by a reference signal stored in the receiver. In this manner, the correlation processing signal is appropriately filtered (integrated), and when one signal is correlated with itself (or

another exact signal), this process is called self-correlation. When one signal is correlated with a different signal, this is called mutual correlation. Under ideal conditions, when a spread spectrum signal is correlated with itself, it should exhibit maximum correlation, in other words, its correlation factor should be maximum (so-called correlation or correlation factor commonly refers to the similarities between the two). When correlated with other signals, however, they should display a minimum correlation, or the smallest correlation factor. The spread spectrum modulation should use this type of coding or sequence for modulation. It is most like itself, and very much unlike other codes or sequences. Because of its similarity, only signals using the same code or sequence for modulation can be correlated at the receiver. Signals which are modulated with different codes or sequences because they are not similar, cannot be correlated at the receiver, and thus multiple access communications is achieved.

What sequences have this characteristic? Clearly, actual noise sequences or real random sequences (because in these sequences, noise pulses are randomly distributed) have these characteristics. However, real noise sequences are difficult to produce and reproduce. They are also difficult to synchronize. Therefore, they cannot actually be used to directly modulate the carrier wave. It has been discovered that artificially created pseudo noise (PN) sequences, when they are long enough, have self correlation factors which are extremely similar to real noise self correlation factors. That is to say, pseudo noise sequences have characteristics similar to noise sequences. Also, pseudo noise sequences are actually periodic and regular, because they can be generated and reproduced by pseudo noise generators. This is why frequency modulated type spread spectrum multiple access uses pseudo noise sequence. In satellite communications, pseudo noise code division multiple access satellite communications mainly uses

the M sequence.

4. Introduction to pseudo noise shift phase keying code division multiple access equipment

The AN/RC-RR used in some satellite communications systems is manufactured by MAGNAVOX Corporation. It can carry four channels of voice, digital information (differential coherence phase shift keying) signal rates are 75, 150, 300, 1200, 2400 and 4800 bytes per second. coding speed is 10 megabytes per second. The bandwidth after spreading is 20 MHz.

NASA tracking and data relay satellite communications (TDRS) system uses the MX-290/291 which is also manufactured by MAGNAVOX. The MX-290 is the modulator and the MX-291 is the demodulator. These are combined to call it the MX-290/291 data-voice pseudo noise modulator demodulator. It provides a half-duplex touch tone voice channel (sound frequency of 300 to 3,500 Hz) or one 2400 or 1200 bytes/second data channel. First, the numerical data signal is DPSK, and voice signals are compressed clock pulse duration modulated (SCPDM), and then they are added to pseudo noise code model 2, and the obtained pseudo noise coded data signal is alternately quaternary modulated by the 70 MHz intermediate frequency. The pseudo noise code is generated by two 13 level maximum length linear sequence generators. The code length is 8191 bytes. The intermediate frequency is 1.228 MHz. It can use switch selection for 8192 type coding for the other stations address, with a spread bandwidth of 2.4 MHz.

There are a number of other similar pieces of equipment. Their parameters will not be listed in this chapter.

III. Pseudo random frequency hopping modulation code division multiple access

How is frequency hopping technology achieved. First, the transmitter uses a feedback shift register code generator to produce the pseudo random code byte flow, and then, it uses grouped pseudo random bytes (using binary numbers) to designate a certain information code element, and it uses a group of numbered frequencies to transmit. The receiver pseudo random code generator produces a pseudo random code byte flow the same as that of the transmitter which is also synchronized with the transmitter pseudo random code byte flow. This serves to make the receiver local oscillator frequency synchronous with the shifts of the received signals, thus making it possible to receive in live time each frequency of the transmitter signal instantaneous frequency hops. How then, how is multiple access accomplished? In a frequency hopping code division multiple access communications network, a number of stations use a common frequency band. Between different stations, because different random coding is used, the instantaneous shifting frequencies are all different, so they cannot receive each other and are only manifest as broad band noise. In this way it is possible to achieve frequency hopping code division multiple access communications. By the same reasoning, the different types of interference will not be able to frequency hop in accordance with the transmitter pseudo noise code instructions, and they are also manifest as similar wide band noise, with only a small portion able to fall with the scope of the instantaneous hopping carrier wave frequency spectrum and be received. Therefore, frequency hopping code division multiple access communications possesses strong counter interference capabilities.

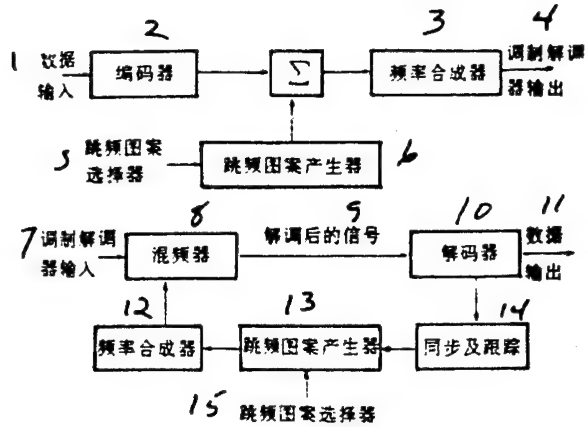
If 12 levels of feedback shift register are used to make up

the pseudo random sequence generator, their cycle period will be $12^{12}-1=4095$, that is, there can be 4095 different 12 byte structures. Each time the register shifts, a 12 byte code element group is sent out, and which carrier frequency used is determined based on the value of this code element group value. In this manner the carrier wave is constantly hopping in accordance with the frequencies directed by the pseudo random sequence generated by the feedback shift register. We call this type of carrier wave the hopping pattern. The transmitter transmission frequencies is modulated using this carrier frequency (hopping pattern).

The United States military "Tactical Communications Satellite"-1 and the and the 'Lincoln Experimental Satellite"-6 satellite communications system used pseudo random frequency hopping code division multiple access. The prototype was called the "TATS" (tactical transmission system". Its transmission data signal rate was 75 bytes per second (fax speed was 100 groups/second, this type of fax is called sol speed digital transmission LDT) and 2400 bytes/second (transmitting sound coded voice, called high speed digital transmission). The spread spectrum of these two speeds were 500 kHz and 10 MHz respectively.

There were two types of TATS modulation: Information modulation used the Reed-Solomon code multiple access frequency shift keying (MFSK), and the carrier wave modulation used frequency jumping over the entire transmission band width in accordance with a certain frequency hopping pattern. The TATS block diagram is shown in Figure 5.

Fig. 5. Block diagram of the TATS modulator and demodulator



1. Data input. 2. Coder. 3. Frequency synthesizer. 4. Modulator demodulator output. 5. Frequency hopping pattern selector. 6. Frequency hopping pattern generator. 7. Modulator demodulator input. 8. Frequency mixer. 9. Demodulated signal. 10. Decoder. 11. Data output. 12. Frequency synthesizer. 13. Frequency hopping pattern generator. 14. Synchronizing and tracking. 15. Frequency hopping pattern selector.

In the TATS, the original signal byte flow is grouped into groups of six bytes, and then converted into an octal Reed-Solomon code, (hereafter referred to as RS code). Each RS code position uses a single frequency, thus forming multiple frequency MFSK. On the other hand, the carrier wave frequency hops within a wide frequency spectrum, with a hopping pattern generated by a frequency hopping pattern generator (shift register). The frequency hop and frequency shift are synchronized, and the two are combined to make the signal transmitted into the atmosphere. The receiving terminal uses a similar shift register to generate the same code to cause hopping of the local oscillator frequency in order to receive the signal.

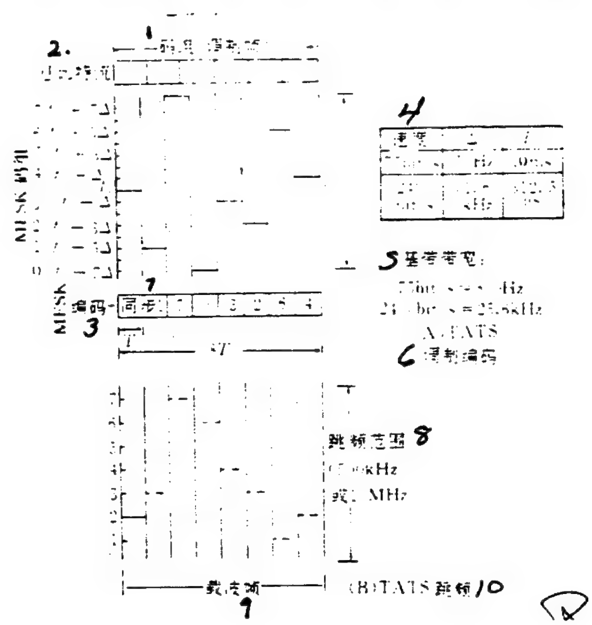
1. Modulation coding

The basis signal formation is: On eight frequencies $1/T_c$

apart a there is a pulse type sine wave with a duration of T_c. Each pulse type sine wave is called one"frame" (or time trough).

Each six byes of the byte flow are combined into one group called one code word (or code group), also called one "modulation frame". These six position binary code words have a total of 64 combinations (2^6). Each frame is composed of seven of these pulse type sine wave sequences, thus becoming multiple frequency shift frequency keying modulation. In addition, at the beginning of each frame a fixed frequency sub-frame is added to synchronize time and frequency. Because each $8T_c$ long MFSK combination only represents six bytes of information, data transmission speed is $6/8T_c$ bytes per second, that is, $0.75/T_c$ bytes per second. When information rate is 75 bytes per second and 2400 bytes per second, T_c is 10 milliseconds and 312.5 microseconds respectively.

Fig. 6. TATS modulation coding and frequency hopping schematic



1. Code groups (modulation frames). 2. Byte flow. 3. Coding. 4. Rate. 5. Base band width. 6. Modulation coding. 7. synchronization. 8. Hopping scope. 9. Carrier wave frame. 10. Frequency hopping.

Figure 6(A) shows the frequency time pattern of a typical code word $(f_c, f_c - 5\Delta, f_c + 7\Delta, f_c - 7\Delta, f_c - \Delta, f_c - 3\Delta, f_c - 5\Delta, f_c + \Delta)$. Using seven pulses to send 64 combinations, there are the following characteristics: Any two code words (code groups) will appear no more than one time on a single time channel (sub-frame, T_c within the pattern) at the same frequency (unsynchronized time channel). At the least, the frequencies of the six time channels are different. Code words generated in this manner using octal Reed-Soloman code and octal frequency instructions generated by this sub-group code are easily achieved using two three byte shift generators. According to analysis, the register shift code independently corrects error in coding, and has maximum not repeat selection. That is, when synchronized, a single code word will not appear at the same time channel using the same frequency more than once. Because of this characteristic, all that is necessary at the receiver terminal is to obtain tow code elements to restore the entire code word information.

At the receiver terminal, an eight channel receiver is used at the end of each T_c pulse to measure the envelope amplitude and to quantify these amplitudes into 16 levels in order to determine the proper frequency for each T_c pulse. The decoder decodes the seven bytes of each frame, comparing the seven bytes input with the 64 seven byte code generated by the decoder, selecting the one most similar, and converting it to a six digit binary code word (information).

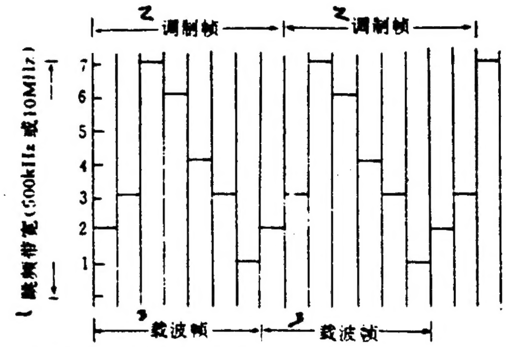
2. Spread spectrum - carrier wave frequency hoping

The spread spectrum of the modulation above is used to generate a new basic frequency or carrier wave f_c for each frame, and then add the selected -7Δ, -5Δ,...., $+7\Delta$. In other words, in each frame a new basic frequency is generated and added onto the

frequency actually transmitted selected by the register shift coding. Looking at Figure 6(b), the actual transmission frequency is expressed as a solid line. This frequency is the frequency hoping carrier wave frequency (dotted line) with the modulation frequency added onto it. This basic frequency is selected from the frequencies evenly distributed within bandwidth of the information channel. The carrier wave hopping pattern is made up of the repeat sequence of the seven frequencies (one carrier wave frame). Because the modulation frame has eight sub-frames, the carrier wave passes through the pattern in a cyclical manner in each sub-frame of each modulation frame (see Figure 7). In this manner, it is possible to ensure frequency diversity when there is selective attenuation.

There are two characteristics to frequency hopping pattern selection: Each pattern can use the entire transmission frequency band: During any possible changes, the numbers overlapping in each pattern are very small. The first characteristic provides diversity capability. This capability is necessary to counter the frequency selective attenuation generated by multipath and high frequency interference. The second characteristic is able to reduce the decoder errors which can be caused by signal channel overlapping. When a number of terminal stations are all communicating, the frequencies used appear to be selected from the uniformly distributed probability within the overall frequency band.

Fig. 7. TATS frequency hopping schematic



跳频图案为:2 3 7 6 4 3 1

Frequency hopping pattern is 2 3 7 6 4 3 1. 1. Frequency hopping band width 500kHz or 10 MHz. 2. Modulation frame. 3. Carrier wave frame.

The frequency hopping pattern is chosen using a group of octal thumb wheel switches. These switches control the shift registers similar to those used in coding, with multiple position shift registers alternately generating carrier frequencies in digital form. Then the data is modulated onto these frequencies. The following chart shows the number of frequency hopping patterns and possible number of carrier waves with different data rates and satellite bandwidths.

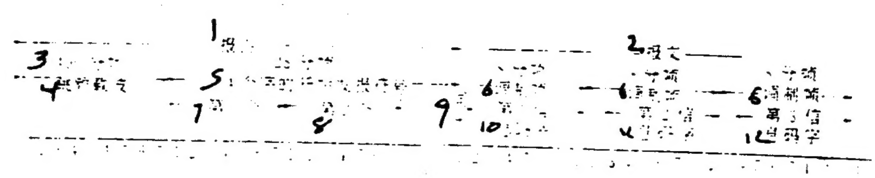
1带 宽	2数据速度	3跳频图案数	4可能的载波数
500 kHz	75 比特/秒 5	4096	256
500 kHz	2400 比特/秒 5	64	16
10 MHz	75 比特/秒 5	4096	4096
10 MHz	2400 比特/秒 5	4096	256

1. Bandwidth. 2. Data rate. 3. Number of frequency hopping patterns. 4. Number of possible carrier waves. 5. Bytes per second.

3. Synchronization

In order to demodulated the signal received, the receiver must generate a local oscillator frequency which has the same hopping pattern (time and frequency pattern) as that of the signal received, so that the difference between the received frequency and the locally oscillated frequency equals the intermediate frequency. The frequency hopping pattern of the received carrier frequency and the local oscillator frequency hopping must be precisely synchronized (precise to about five percent of the subframe). In addition, the receiver local oscillator must also make up for the doppler shift or frequency shift error on the channel. In the receiver there is a synchronizing system. This system constantly searches the beginning for the undeterminate frequency zone, searching for a signal with the required pattern. When it finds this signal, it pulls it in and tracks it, that is, establishes and maintains synchronous time and frequency between the received signal and the local oscillator patterns. Behind this forward search byte is a four word beginning signal (unsynchronized frame). These four words cause the modulator demodulator to enter a digital decoding state. The data form is shown in Figure 8.

Fig. 8. TATS transmission format



1. Report header. 2. Text. 3. Subframes. 4. Frequency hopping carrier wave. 5. Four word begin report symbol. 6. Modulated frame. 7. First 8. Second. 9. Synchronous. 10. First information code word. 11. Second information code word. 12. Third information code word.

The beginning signal search process is a series time search and a parallel (eight signal channels) frequency search. It must cover seven sub-frames of indefinite times and ±400Hz (with doppler effect it is ±800Hz) indefinite frequency ranges. The advance byte length makes it possible for any given speed to have 490 subframes to be search, pulled in and used. At low speeds the search time is five seconds, and for high speeds it is 5/32 of a second.

Pulling in and tracking error signals are combined and provided by the matching filter. The frequency error is obtained by the output levels of the filters used to find the normal central frequency. The time error is obtained by the difference in the central filter output at the beginning and end of synchronized subframes.

After starting to receive, it is possible to use the receiver to maintain the same time and frequency status as the previous communications. In this way it is not necessary for the receiver to go through the search and pull in process with the subsequent communications, and the transmitter can transmit about 1/2 second advance byte, thus greatly reducing the synchronization time. This method can greatly reduce the time required to transmit a short report.

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